Immobilizer and RKE System Design

Version 4

Part 1: Immobilizer Design

Content

Note: At the beginning of every chapter of this presentation an overview about related documents, software and development tools is given. The associated product specifications are not explicitely mentioned.

1

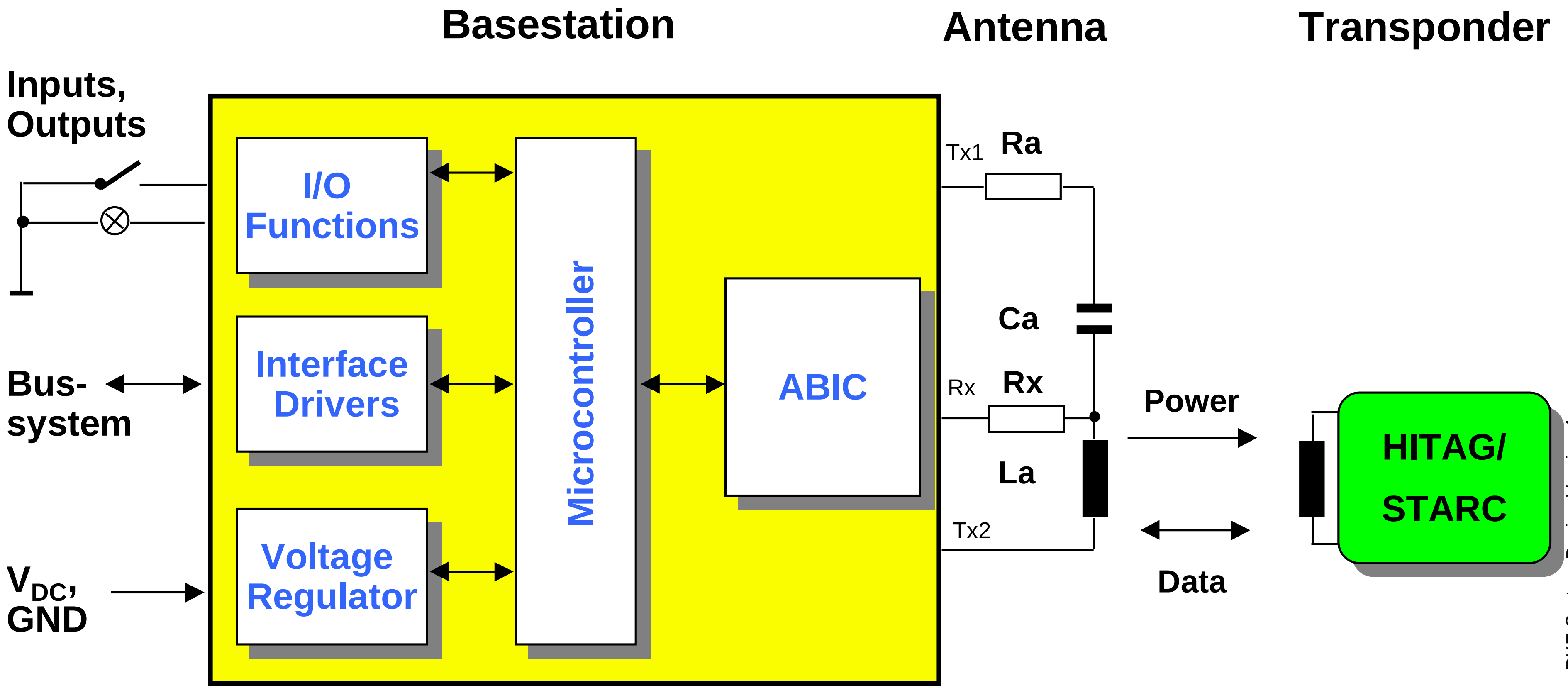
Introduction

- **System configuration**
- Basics of communication

Related Documents, Software and Tools:

- **Application Note AN99075: Designing RF-Identification Basestations with the Advanced Basestation IC PCF7991.**
- **User Manual and Software HSIS/UM9708: Control Software Library for PDF7991AT and PCF7936AS.**
- **User Manual and Tool: Transponder Evaluation and Development Kit (TED-Kit) HSIS/UM9907.**

System Configuration (Principle)



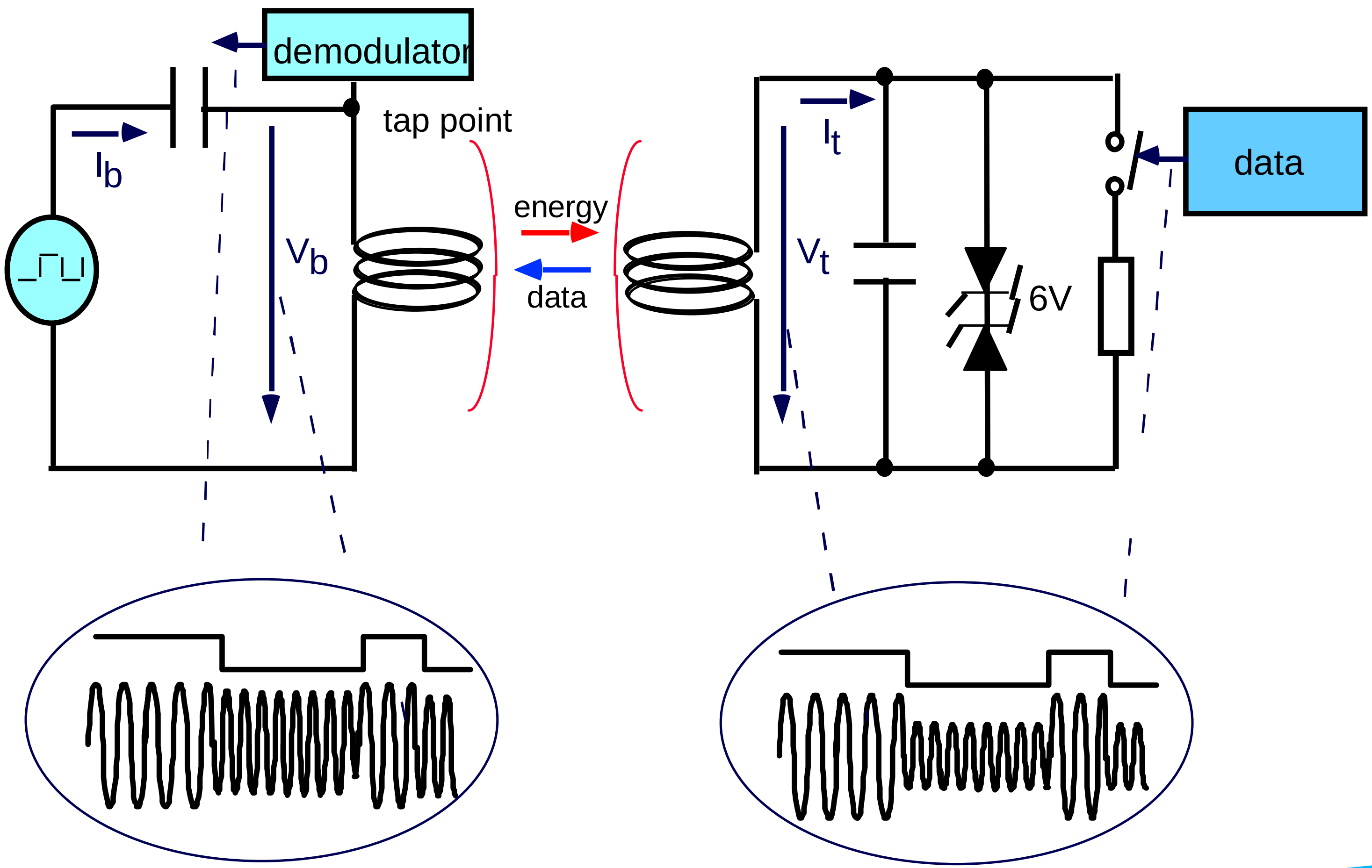
Immo-RKE-System-Design Version 4

1

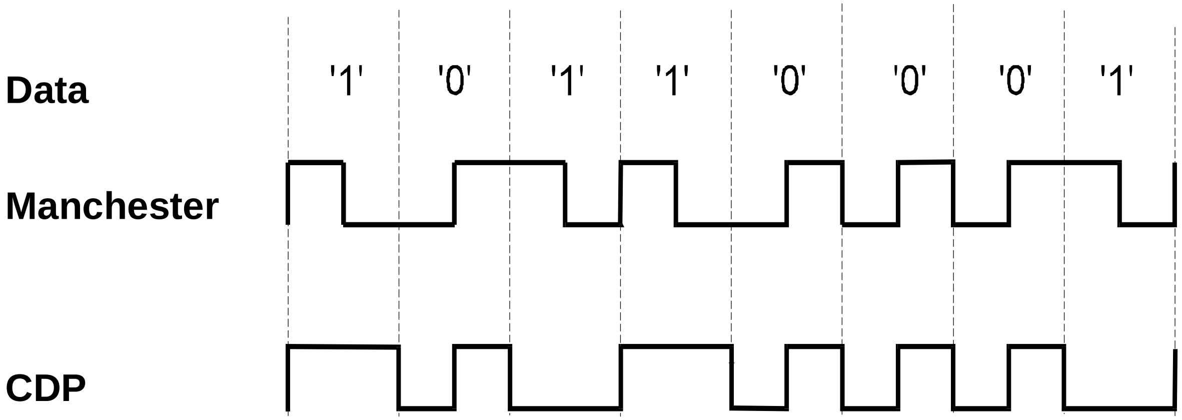
Introduction

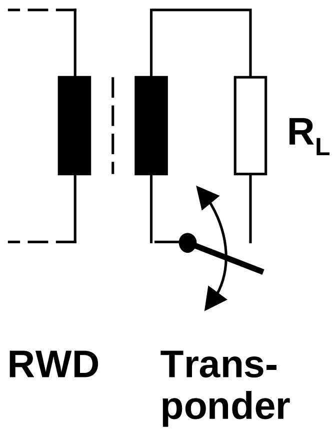
- System configuration
- **Basics of communication**

Principle of Data Transmission from Transponder



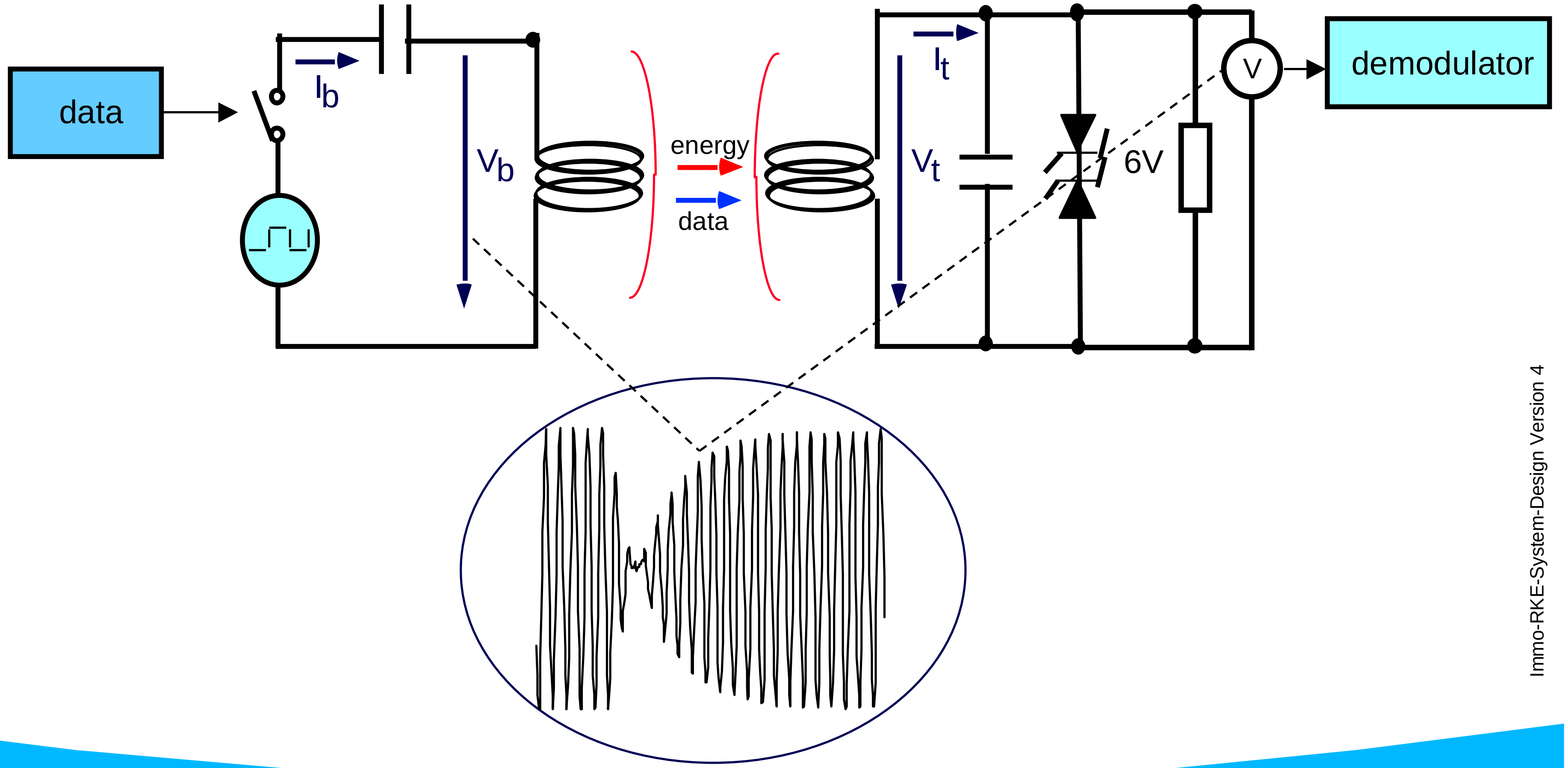
Data Transmission from the Transponder



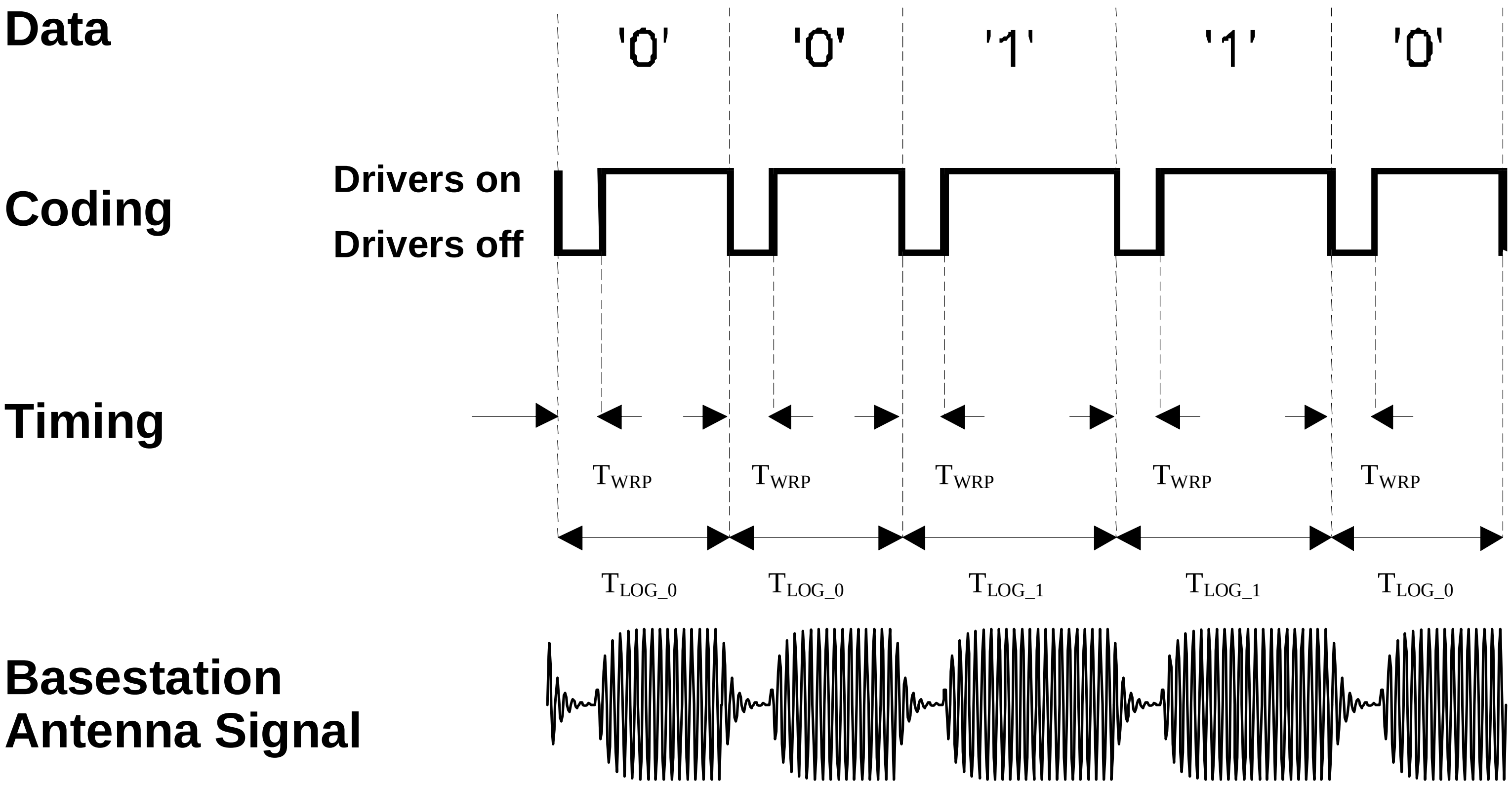


Data rates for Manchester/CDP (HITAG2): 4 kbit/s

Principle of Data Transmission to Transponder



Data Transmission to the Transponder



Duration of T_{WRP} : 4..10 T_0
T_{LOG0} : 18..22 T_0
T_{LOG1} : 26..32 T_0

2

Immobilizer antenna design

- **Physical parameters of antennas**
- Typical design requirements
- Electrical design rules
- Mechanical antenna design

Related Documents, Software and Tools:

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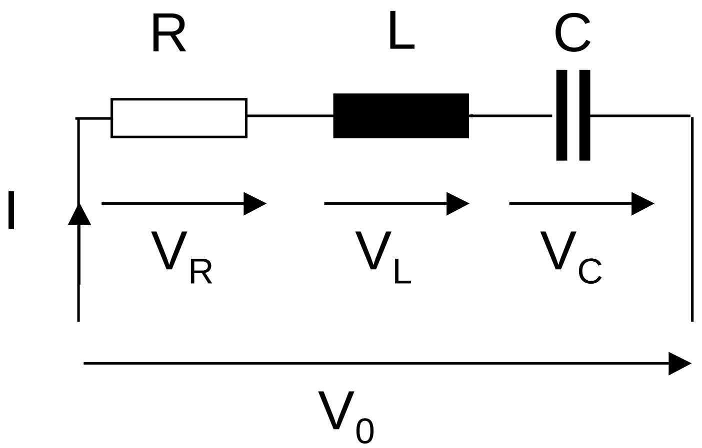
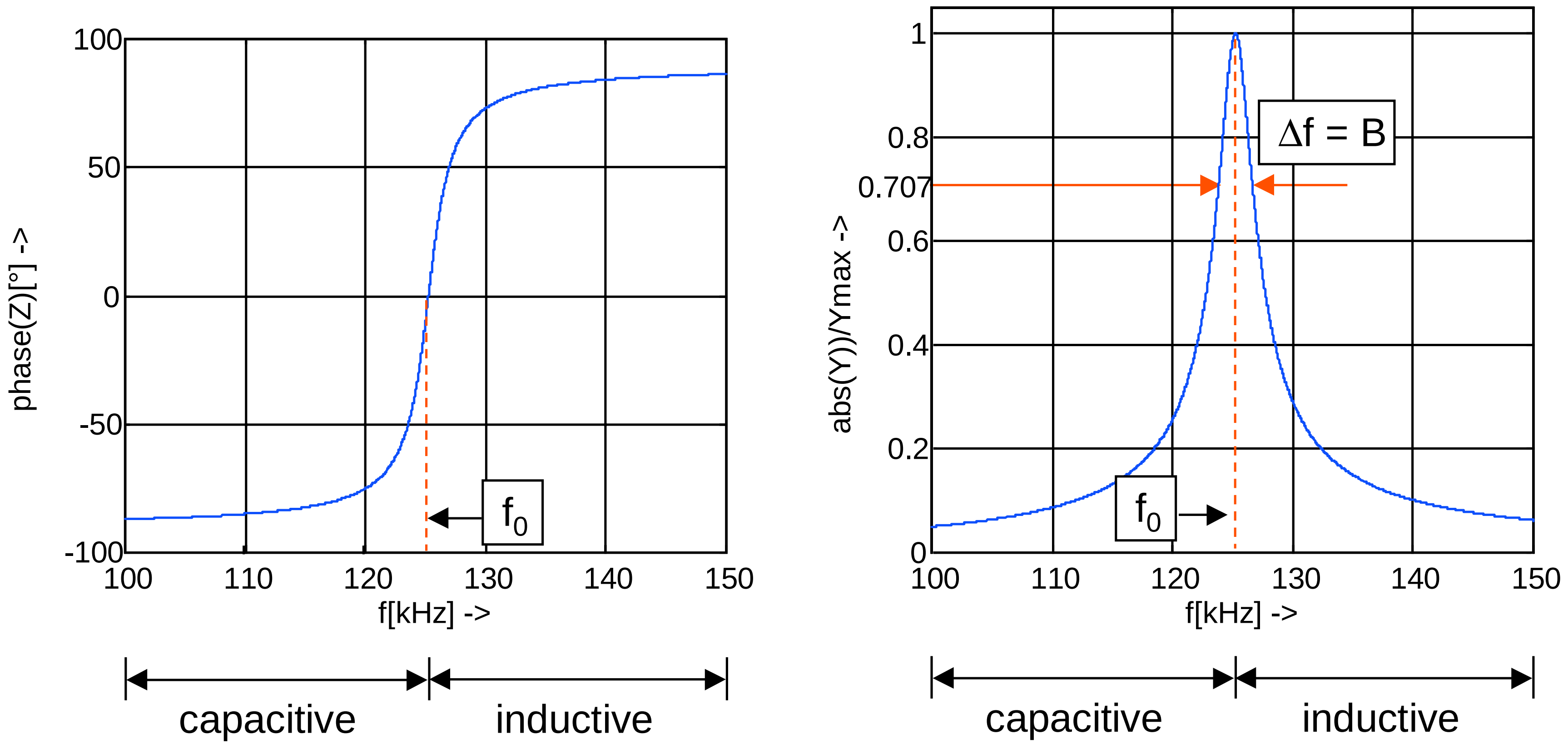
- **Laboratory Report: Questions to the ABIC (PCF7991).**

Series Resonant Circuit (1)



- damping factor: $$\delta = \frac{R}{2 \cdot L}$$
- time constant: $$\tau = \frac{1}{\delta}$$
- quality factor: $$Q = \frac{f_0}{B} = \frac{\omega_0 \cdot L}{R} = \pi \cdot f_0 \cdot \tau$$
- voltages (magnitude): $$V_R = V_0$$ $$V_L = Q \cdot V_0$$ $$V_C = Q \cdot V_0$$

Series Resonant Circuit (2)



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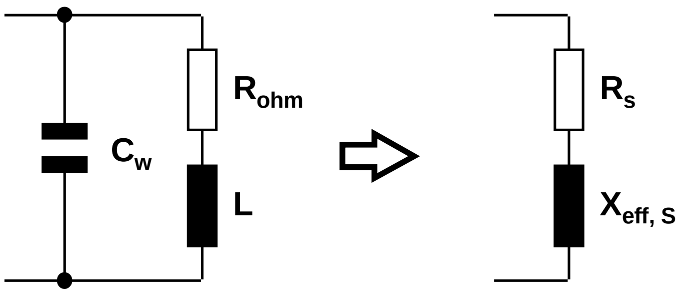
Effective Series Parameter of the Antenna

Physical circuit and serial equivalent circuit of a coil at 125 KHz:



$$R_S = \frac{R_{ohm} \cdot \frac{L}{C_W} - \frac{R_{ohm}}{\omega \cdot C_W} \cdot \left(\omega \cdot L - \frac{1}{\omega \cdot C_W} \right)}{R_{ohm}^2 + \left(\omega \cdot L - \frac{1}{\omega \cdot C_W} \right)^2}$$

$$Q_L = \frac{X_{eff,S}}{R_S}$$

$$X_{eff,S} = -\frac{\frac{R_{ohm}^2}{\omega \cdot C_W} + \frac{L}{C_W} \cdot \left(\omega \cdot L - \frac{1}{\omega \cdot C_W} \right)}{R_{ohm}^2 + \left(\omega \cdot L - \frac{1}{\omega \cdot C_W} \right)^2}$$

R_{ohm}	ohm's resistance of the antenna [Ω]
L	inductance of the antenna [H]
C_W	interwinding capacitance of the antenna [F]
R_S	effective series resistance of the antenna [Ω]
$X_{eff,S}$	effective series reactance of the antenna [Ω]
Q_L	quality factor of the antenna

Practical approach: <u>Measurement</u> of the effective series parameter

Antenna Quality Factor

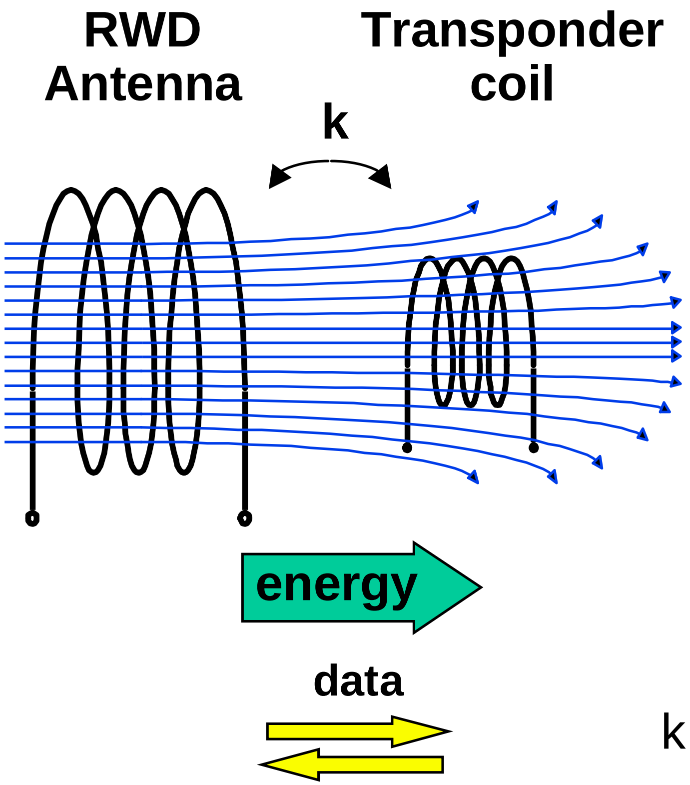
- Definition: $Q_L = X_L/R_L = f_{Res}/B$
- Determines
  - transient and decay times of the antenna signal ⇒ write pulses
  - energy content of the field ⇒ transmission range
- Influenced by
  - losses due to eddy currents in metal in the vicinity of antenna
  - thickness of antenna wire
  - permeability of the core
  - losses due to energy absorption by transponder

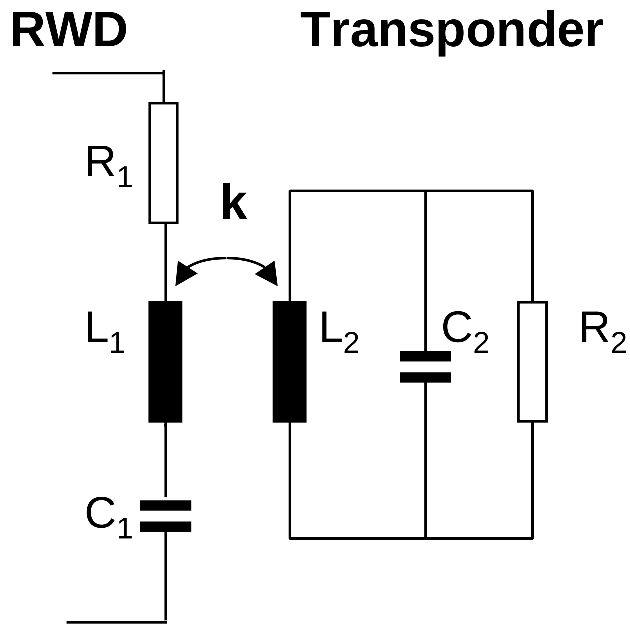
Resonant frequency

- Definition: $$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{L \cdot C}}$$
- Particular value is influenced by:
  - Production tolerances of the antenna components
  - Changes of the component values due to temperature influence
  - Aging of the antenna components
  - High damping factor (low Q) reduces effective resonant frequency:

$$\omega_0^{'} = \sqrt{\omega_0^2 - \delta^2}$$

Coupling factor



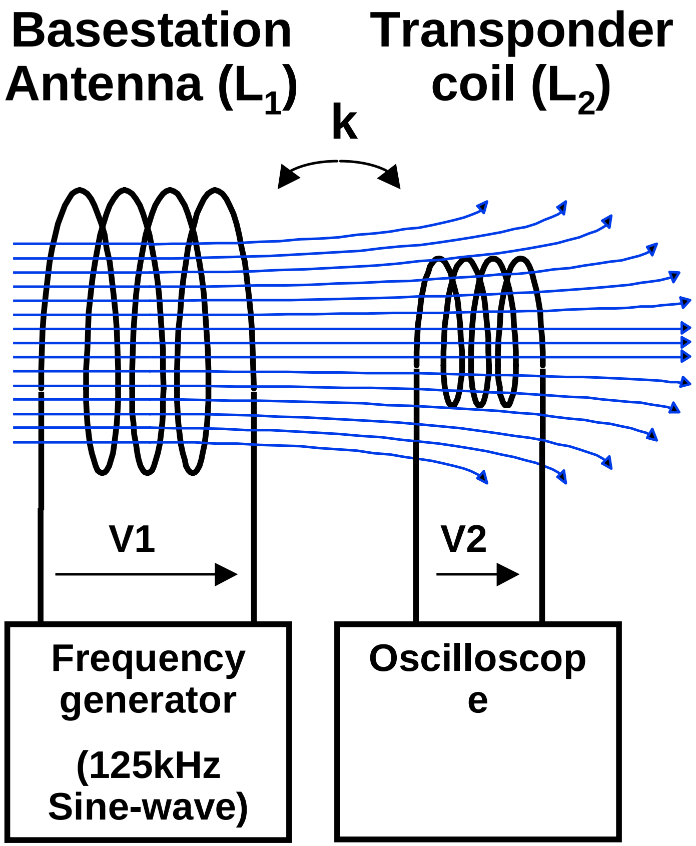


k (coupling factor) depends on the
- amount and
- direction of the magnetic field

Coupling factor

- Describes how many field lines of the basestation antenna are captured by the transponder antenna
- Pure geometric parameter and independent from the antenna inductances
- Relation between coupling factor and system performance is stronger than linear
- Depends on the mechanical antenna design, that is
  - the form and size of the basestation and transponder antennas
  - their placement relative to each other
  - the materials inside or close to the coils
- Since the coupling factor is hard to calculate or to find by simulations, the parameter should be measured

Coupling factor measurement



Conditions:

- **immo-key is placed in home position**
- **transponder is replaced by a transponder coil (molded coil)**
- **all material near the antenna which has influence on the coupling (e.g. metal) must be included for this measurement**
- **Attention: V2 has high impedance, proper probe calibration mandatory. Use low-capacitive probes.**

$$k = \frac{V_2}{V_1} \cdot \sqrt{\frac{L_1}{L_2}} \cdot 100\%$$

2

Immobilizer antenna design

- Physical parameters of antennas
- Typical design requirements
- Electrical design rules
- Mechanical antenna design

Typical design requirements

- Energy supply for transponder function and possible battery charging (e.g. with STARC)
- Specification of the data communication between basestation and transponder:
  - modulated voltage received from the transponder must be sufficient over a wide tolerance range
  - write pulse specification has to be met
- Tolerances specifications of the antenna elements
- EMC requirements:
  - susceptibility
  - radiation
- Communication distance

Typical system parameters

- Basestation antenna parameters:
  - Quality factor range: 5 -15
  - Antenna inductance range: 350 -1200 µH
- Transponder antenna parameters:
  - Quality factor (typ.): 35
  - Antenna inductance (typ.): 2.35 mH
- Coupling factor range: 0.5 - 20 %

2

Immobilizer antenna design

- Physical parameters of antennas
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Electrical design rules (1): General Remarks

- Due to the variety of different requirements and restrictions, the immobilizer antenna design is rather an iterative process
- To optimize the system and to meet all requirements, system simulations should be applied during the design
- Following, some basic design rules are given, to support the optimization process

Electrical design rules (2): Transponder antenna

- For designing a transponder antenna for a normal application of HITAG2+ or STARC1, L=2.35mH, Q=35, as used in the HITAG2 transponder is a good starting value.

- Larger transponder inductances increase the induced voltage at transponder side, however they reduce the modulation voltage seen at the basestation. That means with larger inductances the transponder will be kept running in larger distances, however the distance where the reader stops to demodulate the signal coming back, because of noise, sensitivity limitations and EMI will be reduced.

- Smaller inductances lead to the opposite effect in both cases. Finding the optimum compromise is only possible employing system simulations. However the optimization curve is very flat. Therefore a change from e.g.. 2,3mH to 2.8mH has only a minor effect.

- From the actual experience we'd propose 2.35mH to 3mH.

Electrical design rules (3): Transponder antenna

- A smaller Q will reduce the maximum operating distance, however normally has no high impact in the key home position.
- If a STARC1-system is designed for battery charging, smaller inductances shall be applied to allow higher currents (around 1mH). Optimization has to be done by simulations.
- The models for STARC2 are still under development. At the moment we propose also 2.35mH as a starting value for optimization of the transponder inductance.
- The size and volume of the ferrite core influences the coupling factor. Higher volumes lead to higher coupling, however this effect is only proportional to the 3rd root of the volume.

2

Immobilizer antenna design

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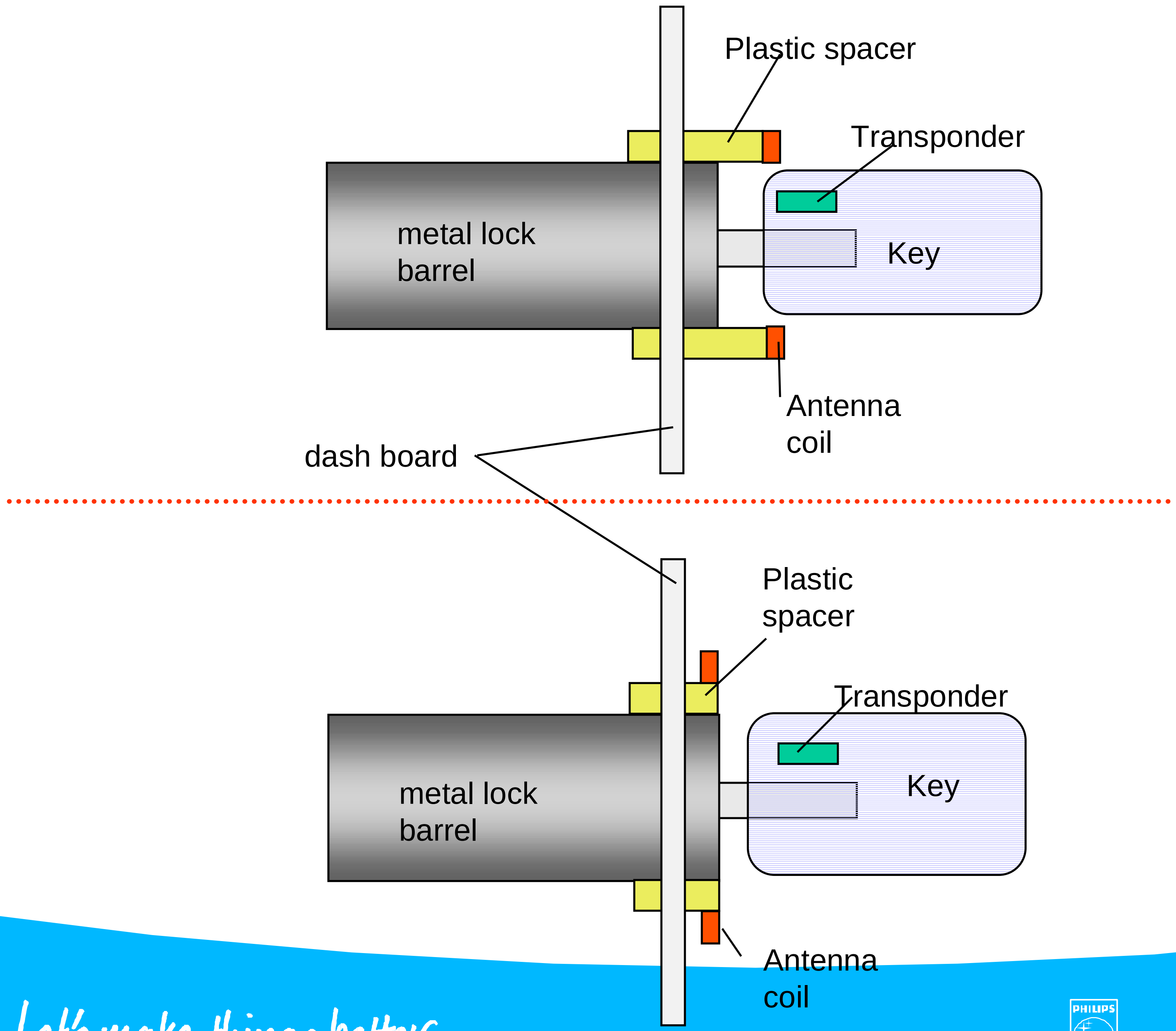
Mechanical Design: Configurations



The upper design example normally results in higher coupling factors

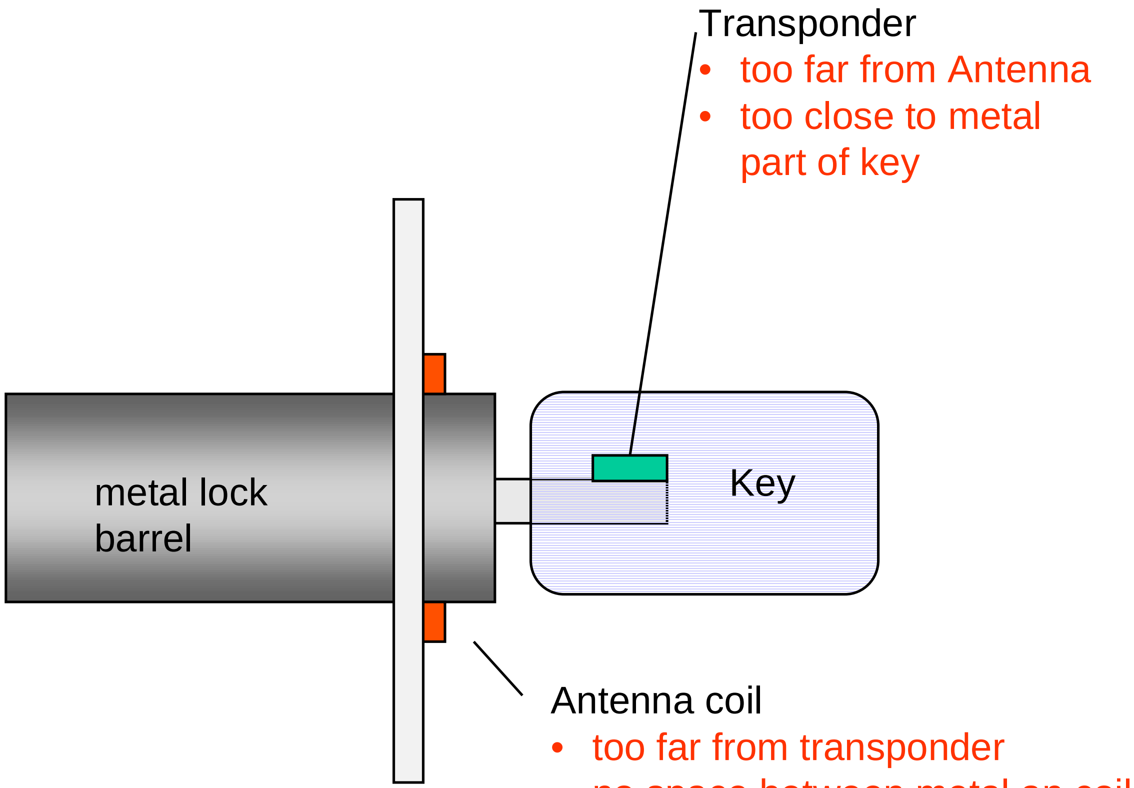
Mechanical Design Rules (1)

- Keep some distance between metal lock barrel and antenna coil by a plastic spacer part not to dissipate too much field energy in form of eddy currents into the metal.
- Place the transponder in axial direction as close to the antenna as possible or even inside.
- The distance of the transponder in radial direction from the lock barrel middle axis must be smaller than the inner coil winding radius.
- Inside the key, the transponder should be placed as far as possible from the key metal parts but as close as possible towards the antenna coil.

Mechanical Design Rules (2)

- Metal parts of the dash board should be as far as possible away from the antenna.
- The coupling factor should be optimized by practical experiments with different coils, coil positions, transponder positions and transponder angles relative to the middle axis by powering the antenna coil with a 125kHz sine frequency generator and measuring the induced voltage in a molded coil in transponder position before finishing the lock design. Optimization by analytical calculations is hardly possible.

Bad Mechanical Design Example



Mechanical Requirements

- The mechanical stability of the ferrite coil of the transponder antenna, also related to it's packaging and the way the part is soldered to the PCB, is very important. This issue should be addressed by fall tests with coils soldered to the final PCB.

- The temperature and humidity drift of the inductance is a very important issue as well as a small manufacturing tolerance. The overall tolerance should be in the ±3% range, at least for systems with weak coupling.

- If water can enter the key housing and short the coil or the interconnection to the transponder IC, the system will fail. Therefore, water protection by molding, lacquering or a water resistant sealed key is important.

3

ABIC basestation design and optimization

- **Design and adaptation of the resonant circuit to the ABIC**
- Implementation of the AST algorithm
- Configuration of the ABIC
- Electrical verification and debugging

Related Documents, Software and Tools:

- **Application Note AN99075: Designing RF-Identification Basestations with the Advanced Basestation IC PCF7991.**
- **Laboratory Report: Proposal for a Circuit Design and PCB-Layout for the PCF7991 (ABIC)**
- **User Manual and Tool: Transponder Evaluation and Development Kit (TED-Kit) HSIS/UM9907.**

Basic specifications for ABIC based systems

- ABIC:
- maximum antenna current: $I_{max,p}$ = 200 mA_p (Burst mode: 400 mA_p)
- output voltage: V_{out} = 5V * 4/π = 6.3 V_p
- maximum Rx-pin-input voltage: $V_{Rx,p}$ = 7..8 V_p

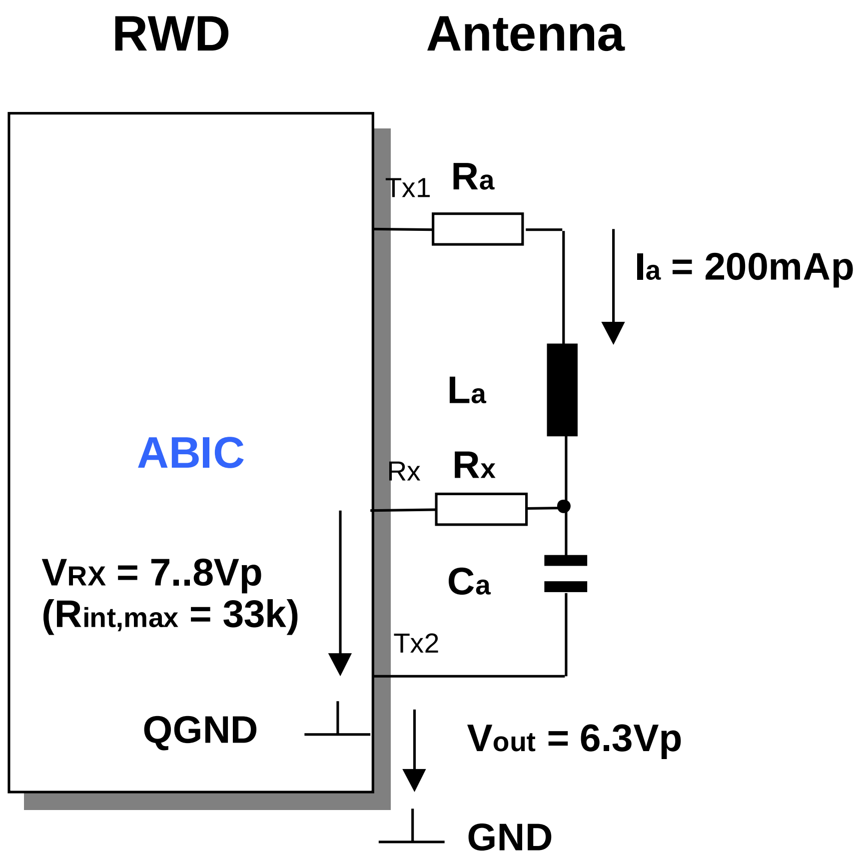
- basestation inductance value range: L = 350 .. 1200 µH

- basestation quality factor range: Q = 5 .. 15

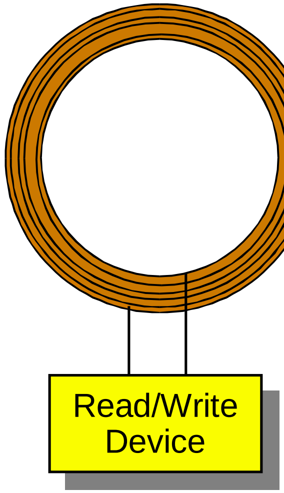
Basestation Design Example

- Choose L_a = 400µH
- $C_a = 1 / L_a / (2 \pi f_{res})^2$ = 4nF
- $R_a = V_{out} / I_a$ = 32 Ohms
- $Q = 2 \pi f_{res} L_a / R_a$ => Q = 10 (in range)
- $V_{Rx} = V_{tap} R_{int,max} / (R_x + R_{int,max})$ => R_x

  ($V_{tap} = Q V_{out}$ = 63Vp)
- k = 1% (measured)
- Coil Design...



Basestation Coil Design



$$L = 4 \cdot r \cdot \pi \cdot \ln\left(\frac{2 \cdot r \cdot \pi}{d}\right) \cdot N_A^{1,85}$$

L	inductance [nH]
r	antenna radius [cm]
d	wire diameter [cm]
N_A	number of turns

Inductance value, calculated by this formula, is strongly influenced by metal and ferrite in the vicinity of the coil.

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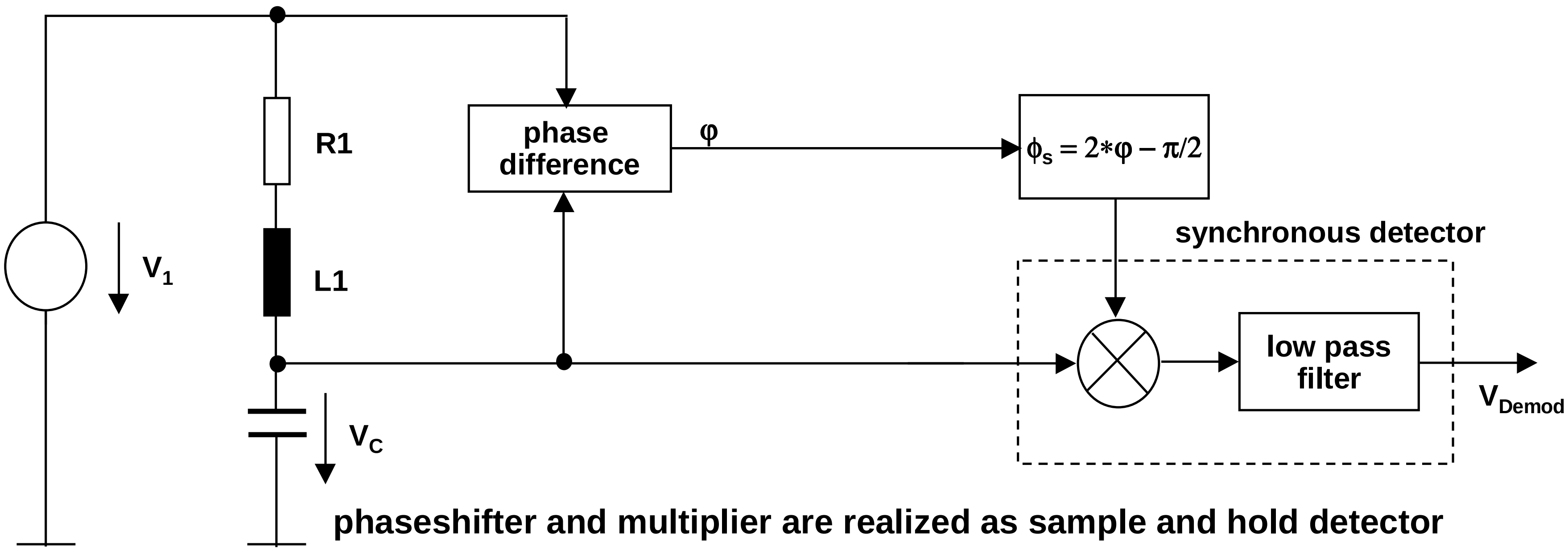
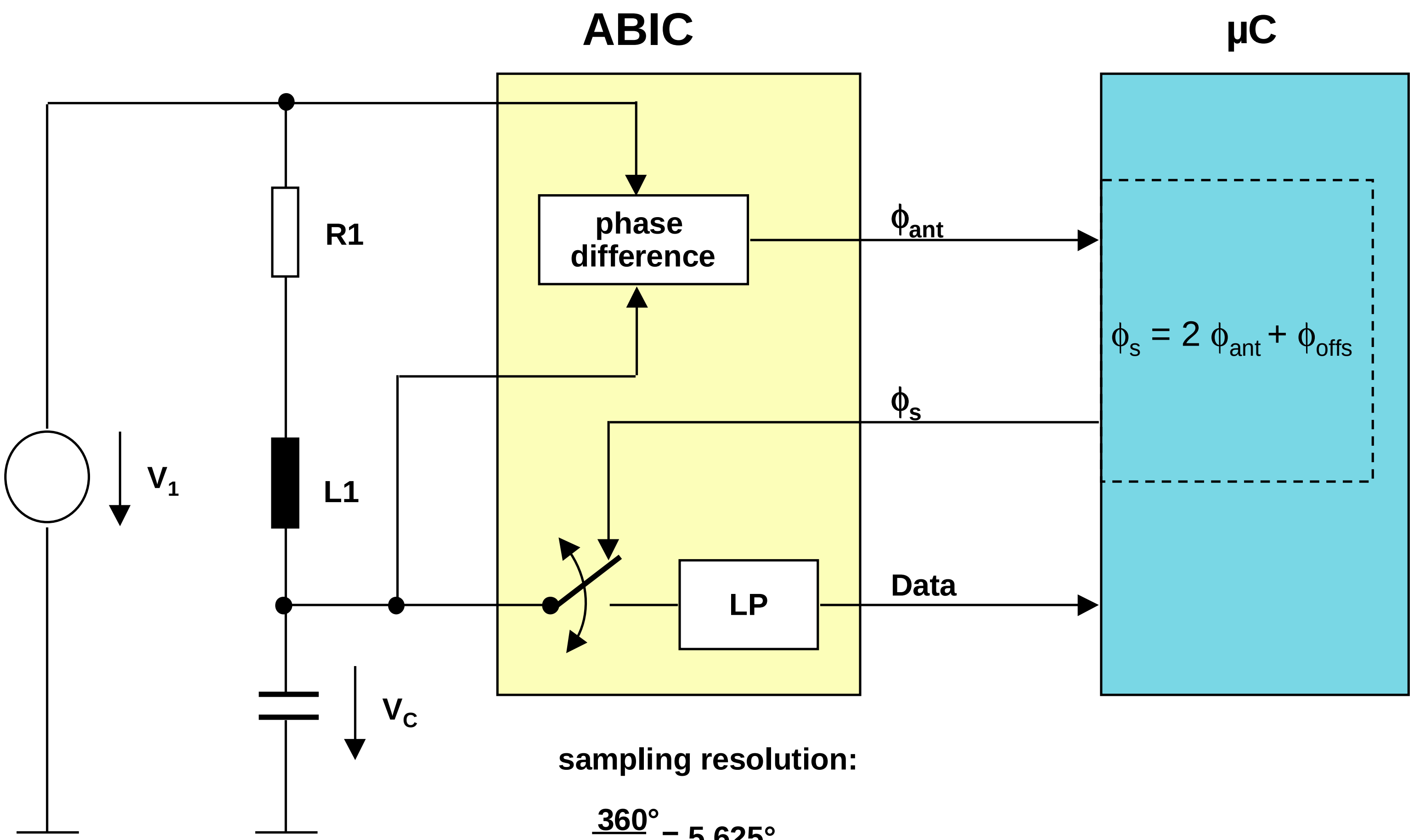
Adaptive-Sampling-Time Principle



- **only one demodulator ⇨ good price/performance ratio**
- **correct demodulation from the first bit on ⇨ short authentication time**
- **demodulation of only one data stream required ⇨ low µC calculation power, low µC price**

AST Implementation



sampling resolution:

$$\frac{360°}{64} = 5{,}625°$$

Microcontroller Function

```
void Ast_Adjust (UBYTE t_offset)

{
        UBYTE t_antenna;

        t_antenna = READ_PHASE();
        t_antenna <<= 1;                // multiply by 2
        t_antenna += t_offset;          // add compensation constant
        t_antenna &= 0x3F;              // mask out
        SET_SAMPLING_TIME(t_antenna);
}
```

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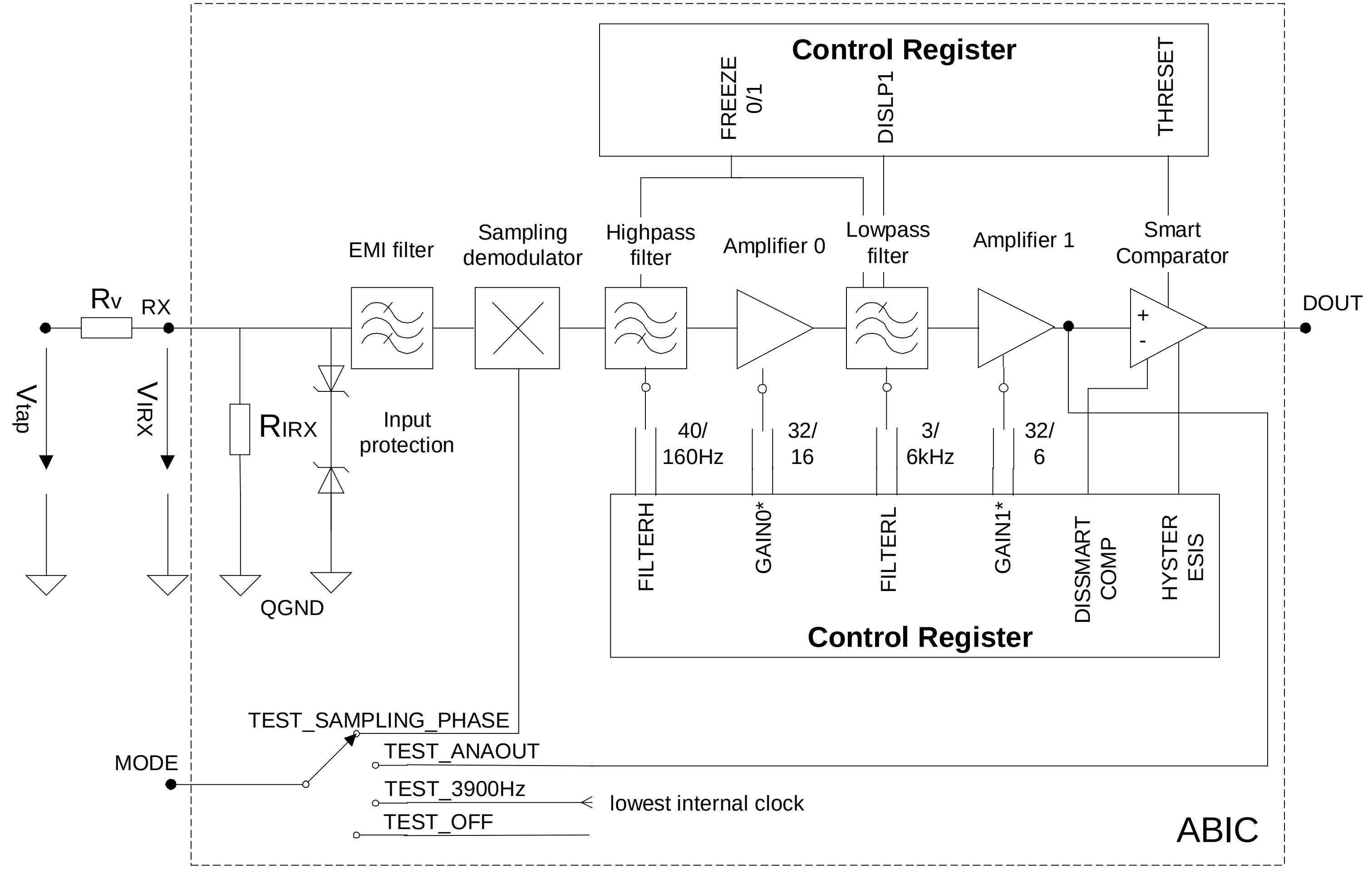
Extended block diagram of the ABIC



*gain values without filter attenuation

Configuration of the ABIC

Contents of the Configuration Pages

Page:	Bit 0			Bit 3
0	GAIN1	GAIN0	FILTERH	FILTERL
1	PD_MODE	PD	HYSTERESIS	TXDIS
2	THRESET	ACQAMP	FREEZE1	FREEZE0
3	DISLP1	DISSMART-COMP	FSEL1	FSEL0

- one config page contains 4 bit
- realized as RAM (not EEPROM)

Configuration of the ABIC

Optimum filter settings for HITAG2/STARC based systems

- The following filter settings are adapted to the spectral properties of the Manchester/CDP code with a data rate of 4 kBit/s
- Main low pass cutoff frequency: 6k Hz (FILTERL = 1)
- Main high pass cutoff frequency: 160 Hz (FILTERH = 1)
- Main low pass is enabled (DISLP1 = 0)

Optimization of the ABIC gain settings

- we propose to choose the demodulator gain in order to have at least a voltage of 2Vpp demodulated signal at the input of the smart comparator (check TEST_ANAOUT as explained in this training) for the weakest baseband signal expected in the given system
- 2 mVpp would correspond to the minimum receiver sensitivity multiplied by the maximum gain of the ABIC
- the weakest baseband signal occurs for the worst case combination of transponder resonant frequency tolerance and basestation resonant frequency tolerance

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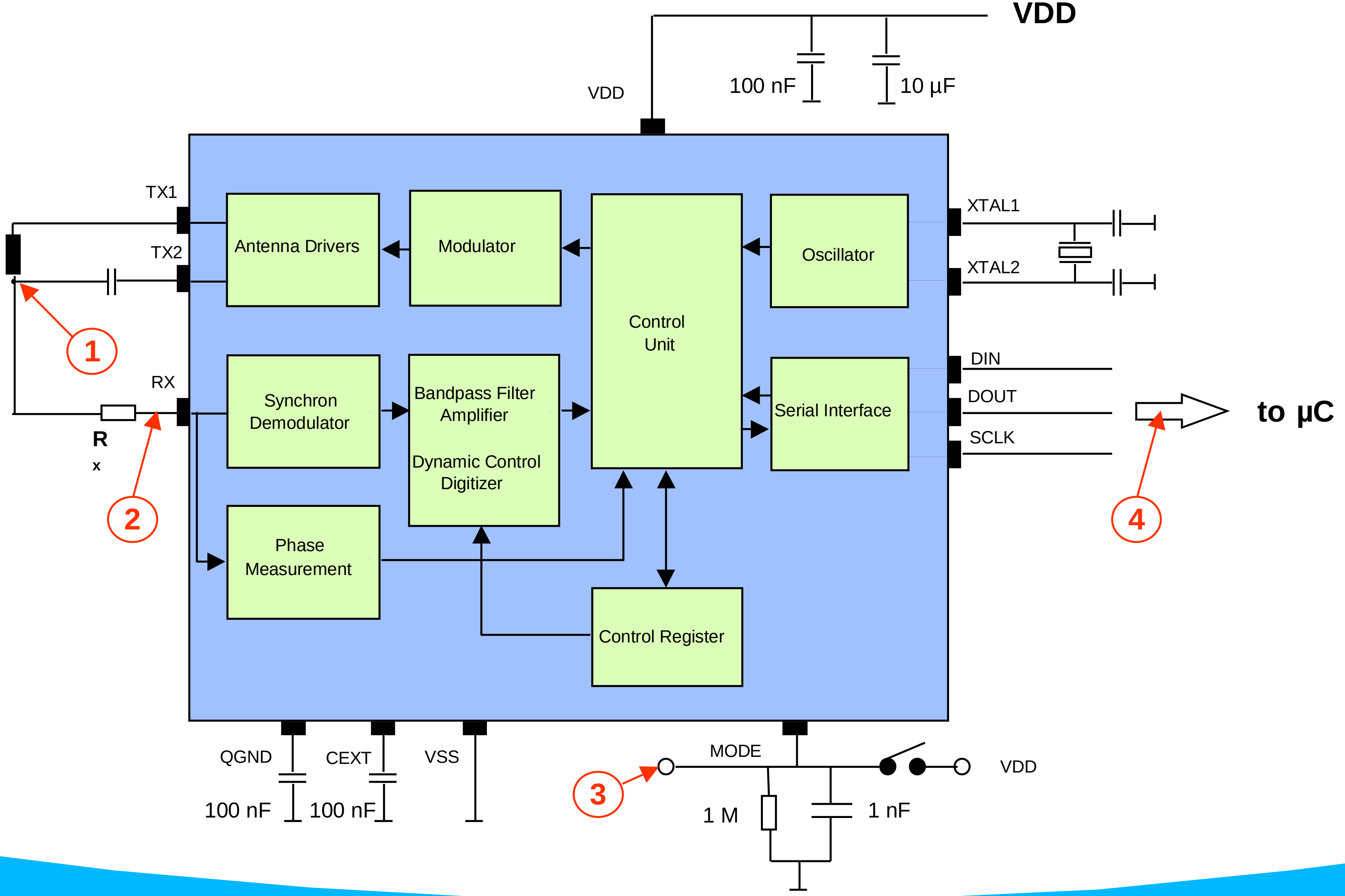
ABIC Block Diagram



4

System verification

- **Tolerance field verification by simulation**
- Tolerance field verification by measurement
- Temperature, humidity and functional tests
- EMC measurements and optimization

Related Documents, Software and Tools:

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Tolerance Field Diagrams

- Verification method during and after design phase
- Due to production and temperature tolerances, the resonant frequencies of transponder and basestation antenna are changed
- In practice, nearly all combinations of transponder and basestation resonant frequencies are possible
- Tolerance field shows the safe operating area of the system in means of transponder and basestation tolerance
- Tolerance fields can be determined in two ways
  - by simulation
  - by measurements

Philips Tolerance Field Simulation Program

There are two different tolerance fields calculated, as function of the resonant frequency of two inductively coupled resonant circuits:

- the energy transfer function
- the amplitude of the demodulated data received from the transponder

The following restrictions apply:

- Calculation is done in the Frequency domain; transients in time domain are neglected
- the calculation is restricted to the fundamental; higher harmonics are neglected
- modelling the transponder by pure ohmic load (power dissipation and load modulation)
- V/I transfer function of the transponder is linearized (pice-wise)
- modelling the demodulator of the basestation by math. model

Simulation Capabilities

Important Note:

- Due to the given restrictions, the simulations can not replace practical measurements and qualification of the transponder system
- Measurements, which include temperature effects, aging and other parameter of the used devices, have to be done in addition to the following simulations

Following, <u>one option</u> to do worst case simulations with the PHILIPS simulation tool ‚TOLSIMU‘ is shown on an example with practical values.

Example (1): Given Parameters

System:

- k = 1.8% (min)

Base station: PCF7991AT (ABIC) :

- V_{DD} = 4.9V - 5.1V (5V +- 2%)
- R_{OTX} = 0 - 7 Ohm (Driver resistance ABIC in full bridge)

Base station antenna:

- L = 601µH - 651µH
- R_{Reihe} = 29.1 - 29.7 Ohm
- $R_{CU,FE}$ = 22 - 24.4 Ohm

Example (2): Derived Parameters

Base station antenna quality factor:

- $Q1 = (2^* PI * 125e3 * L) / (R_{Reihe} + R_{OTX} + R_{CU,FE})$
- $Q1_{min} = (2^* PI * 125e3 * 601e-6) / (29.7 + 7 + 24,4)$
- $Q1_{min} = 7.72$
- $Q1_{max} = (2^* PI * 125e3 * 651e-6) / (29.1 + 0 + 22)$
- $Q1_{max} = 10$

External Resistor at Rx:

- $R_{V,MIN} = R_{IRX,MAX} * ((V_{DD,MAX} *4/PI * Q1_{max}) / V_{IRX,MAX} - 1)$
- $R_{V,MIN} = 235$ kOhm
- $\Rightarrow R_{V,NOM} = 270$ kOhm (choosen according to IEC-E24, 2% Toleranz)

Example (3): Derived Parameters

Minimal amplitude of the modulated voltage at base station antenna:

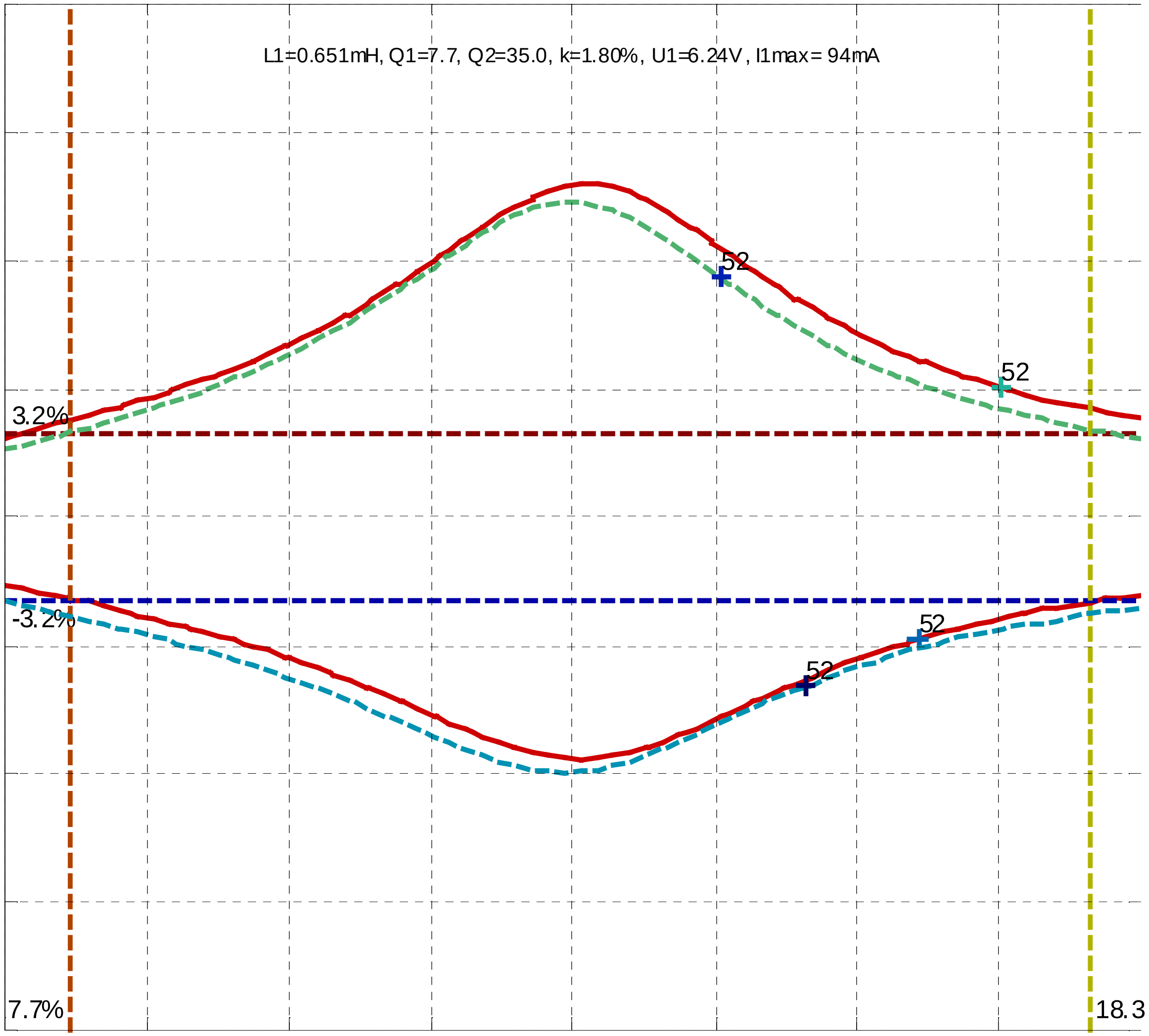
- V_{RX} = 3 mV (peak) (ABIC gain at 1000)
- V_{MOD} = ($R_{V,MAX}$ / $R_{IRX,MIN}$ + 1)* V_{RX}
- V_{MOD} = 51.6 mV (peak)

Example (4): Simulation 1, Demodulation of TXP data

Used simulation parameters:

- k = 1.8%
- f_{OSC} = 125kHz (+-0.3% => two plots in one diagram)
- V_{DD} = 4.9V
- L = 651
- Q1 = 7.72
- V_{MOD} = 51.6 mV (display the 52mV line at tap point)
- Standard HITAG2 Transponder Model

Example (5): Simulation 1, Demodulation of TXP data

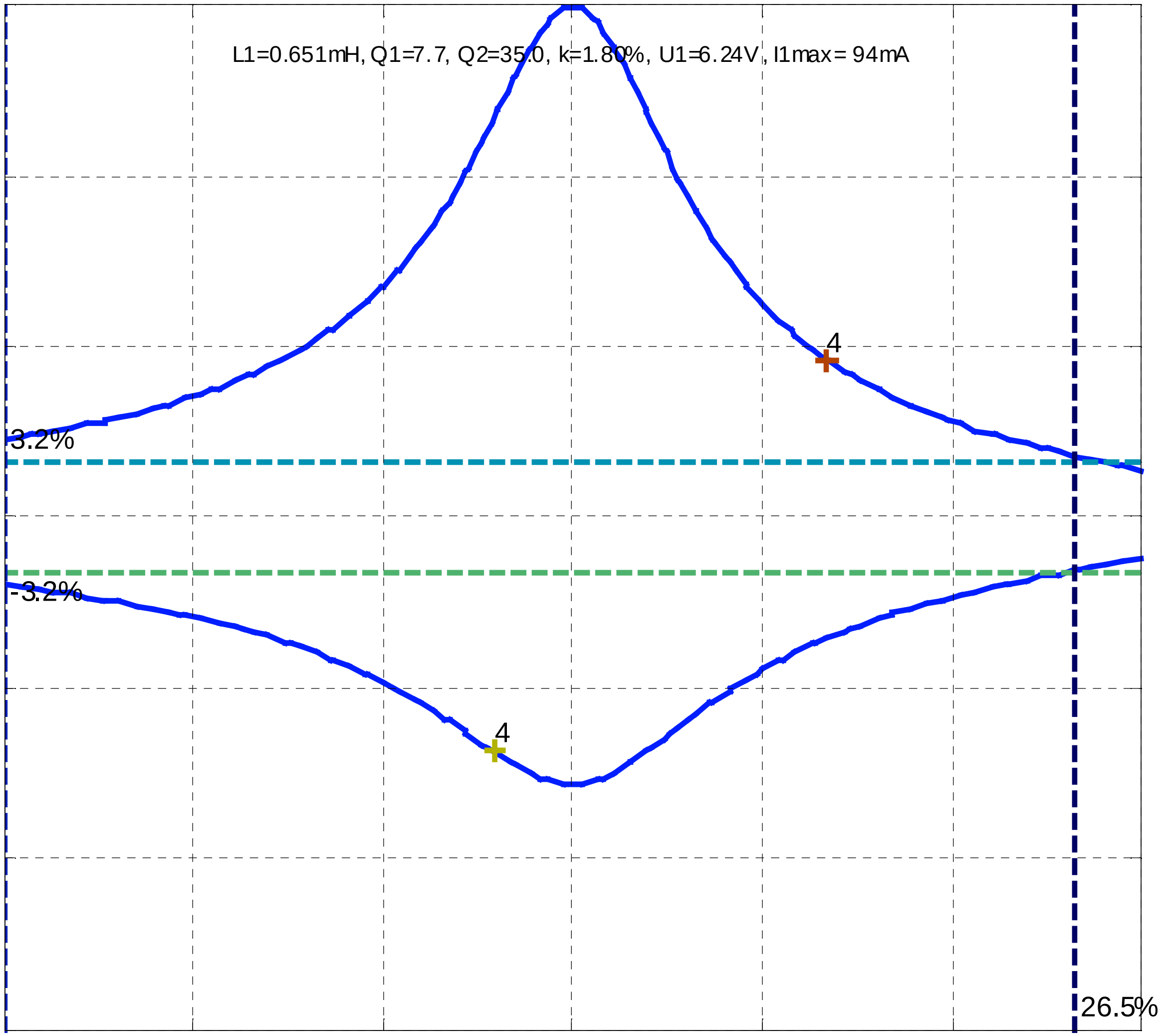


Example (6): Simulation 2, Energy transfer

Used simulation parameters:

- k = 1.8%
- V_{DD} = 4.9V
- L = 651µH
- Q1 = 7,72
- Energy: Standard HITAG2-Model

Example (7): Simulation 2, Energy transfer



4

System verification

- Tolerance field verification by simulation
- **Tolerance field verification by measurement**
- Temperature, humidity and functional tests
- EMC measurements and optimization

Related Documents, Software and Tools:

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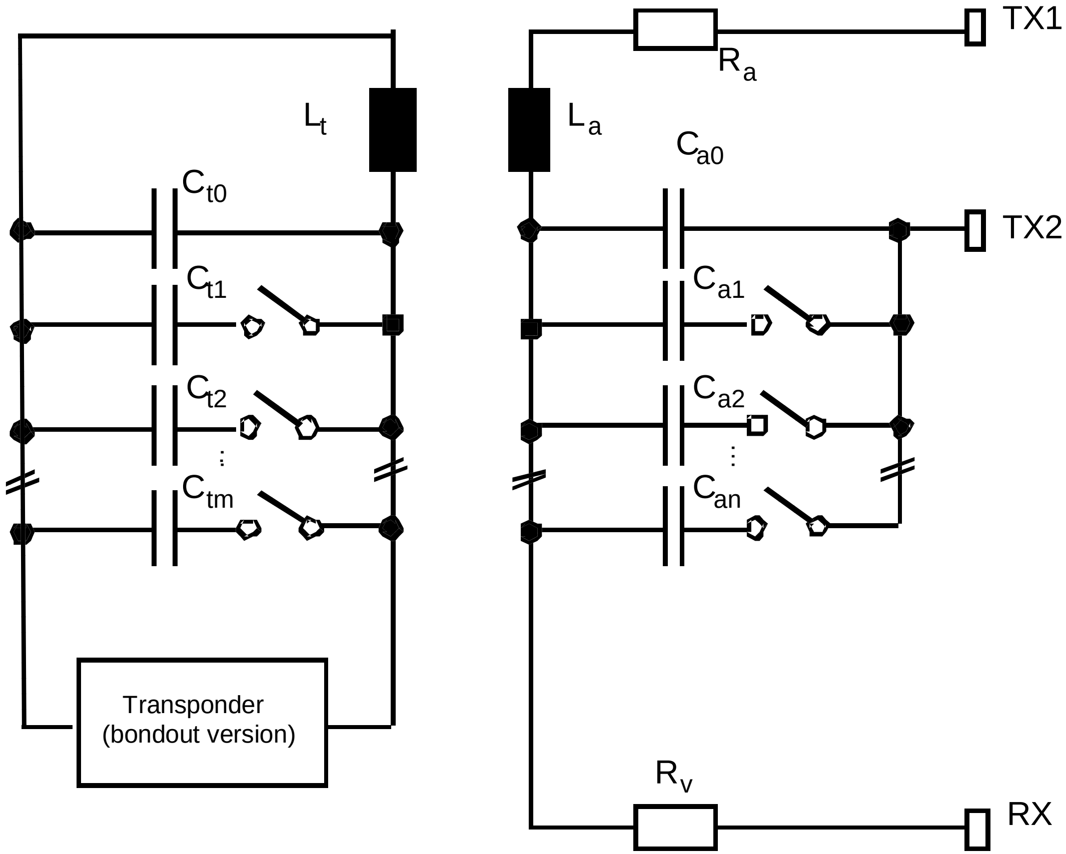
Tolerance Field Measurement Setup (Principle)



4

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- **Temperature, humidity and functional tests**
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Related Documents, Software and Tools:

- **Important information about relevant tests and test conditions can be found in the '*Product Qualification Packages'* of the particular products.**

Temperature, humidity and functional tests

- Temperature and humidity chamber tests should be done according to the maximum operating conditions given in the module specification
- Temperature and humidity chamber tests should be done with ALL transponder system components included (basestation electronics, immobilizer coil and transponder)
- Functional tests should be done with a larger number of devices to get statistically relevant results
- The ICs used in the tested modules should be taken from different batches

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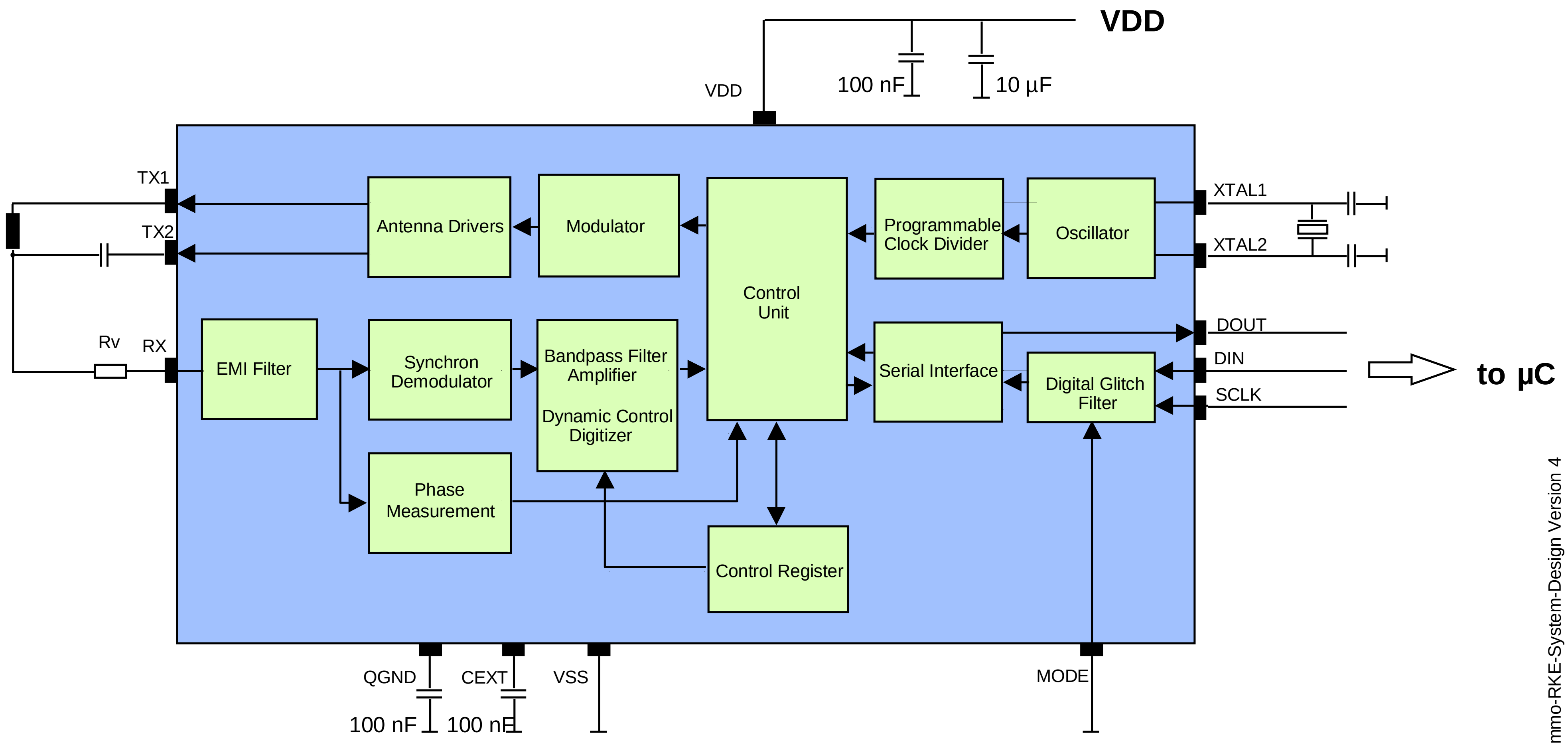
- **Laboratory Report: Questions to the ABIC (PCF7991).**

ABIC-EMC guidelines (1)



ABIC-EMC guidelines (2)

- It is extraordinary important to place Rv as close as possible to the RX-pin for optimum EMI-performance.
- The power supply shall be bypassed (de-coupled) via a 10µF or larger capacitor in parallel to a 100nF capacitor
- For bypassing the internal analog virtual ground (~2V), a 100nF capacitor has to be connected from the QGND-pin to the VSS-pin. This capacitor connection should be low impedance and close to the IC.
- Another 100nF capacitor is connected from CEXT to VSS, which is needed for the 2nd high pass filter. This capacitor connection should be low impedance and close to the IC too.
- It is recommended to place a guard ring at the QGND potential around the CEXT-pin - capacitor lead, to prevent leakage currents into CEXT.
- The usage of the internal ABIC glitch filters should be considered depending on the particular application.

ABIC-EMC guidelines (3)

- The value of the pull-up resistors of the serial interface (DIN, DOUT, SCLK) should be chosen to minimize the influence of external disturbers on these lines. This can be verified during measurements of these signals under EMC conditions.

- Increasing the Q-factor of the basestation antenna to improve the selectivity of the basestation resonant circuit.

Please read the relating chapters of the ABIC application note very carefully, which provide additional hints and background information concerning the presented topics.

Hints for EM-Susceptibility measurements (1)

Separate measurements at the ABIC-MODE-pin in *TEST_ANAOUT* -mode under the following conditions:

- A) the demodulated signal amplitude (without disturber, only transponder modulation)
- B) the 'demodulated' noise amplitude (only disturber active to measure susceptibility)
- By doing these measurements the *signal to noise ratio* (depending on the disturber carrier frequency) of the system can be

Doing measurements on the system with an oscilloscope using the *post-trigger* mode:

- In case of a communication error during EMC-measurements, a post-trigger is generated by the basestation application software
- The other channels of the oscilloscope are connected to important signals like RX, DIN, DOUT, SCLK and VDD
- By this, the prehistory of the error can be observed and countermeasures can be done
- **Note:** Measurements during EMC tests may have strong influence on the system performance and EMC behaviour, due to the susceptibility of the measurement probes and cables.

Hints for EM-Susceptibility measurements (2)

Doing measurements on the system with *reduced* disturber field strength:

- Susceptibility can be measured with e.g. $E_{reduced}$ = 50V/m instead of $E_{nominal}$ = 100V/m (values depend on the used EMC specification)
- This can be done, to find the most critical disturber frequencies. Note: Provided that after EMC-measurements only go/no-go information is available (measurement with fixed disturber field strength).
- This information can then be used for example to design optimised adapted filters.

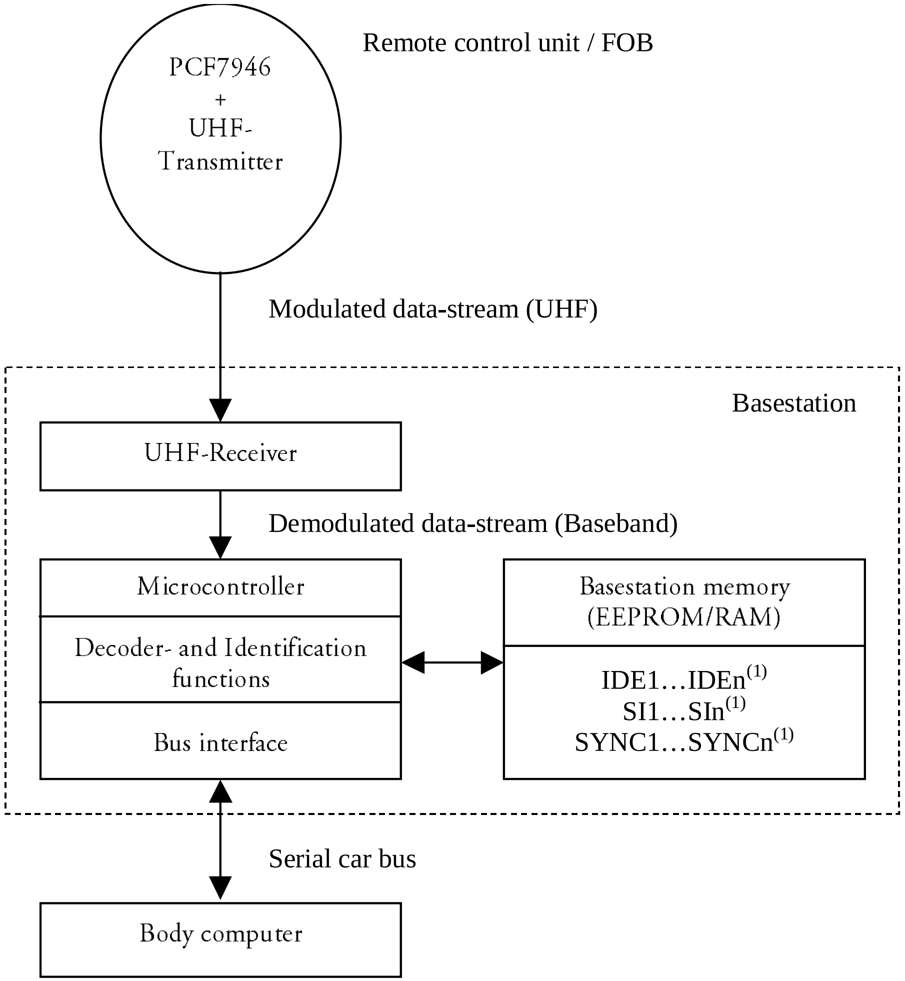
Part 2: RKE Implementation for HITAG2+ based sytems

Content

Related Documents, Software and Tools:

- **Application Note AN00041: Implementation of remote keyless entry with the PCF7946.**
- **User manual and Software CAS/UM0101: HITAG2 / HITAG2+ Security Algorithm for 8 bit microcontrollers.**
- **User Manual and Tool: Transponder Evaluation and Development Kit (TED-Kit) HSIS/UM9907.**

Block diagram of an RKE system (example)



(1) These values must be stored in the basestation memory for each car remote control (1..n) separately

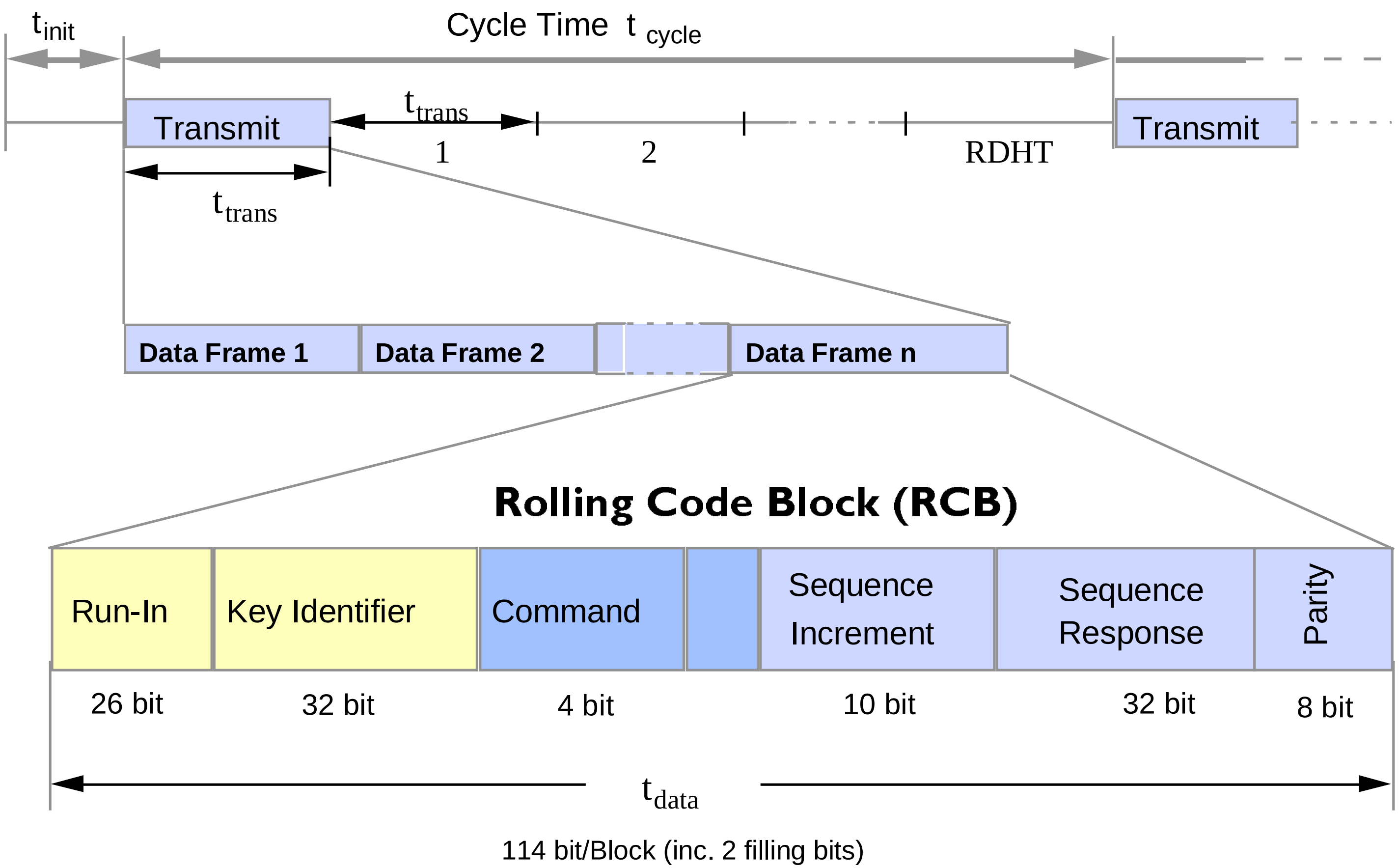
Design of an remote data telegram (1)

Typical system requirements

- the maximum receiver wake up time including the polling cycle of the UHF-receiver for a typical self polling system $t_{RECMAX} < 25$ ms
- the system response time to a button pressing $t_{RES} < 100$ ms
- demand of redundancy of transmitted data blocks to get more system tolerance in case of transmission errors or external disturbances
- low power consumption of the battery powered remote control unit
- specification of the LED blink frequency and its duty cycle
- fast and save detection of button release (e.g. for comfort functions like ‘open car windows’)
- prevention of discharging the battery due to unintentional button pressing
- specification of a particular transmitter circuit

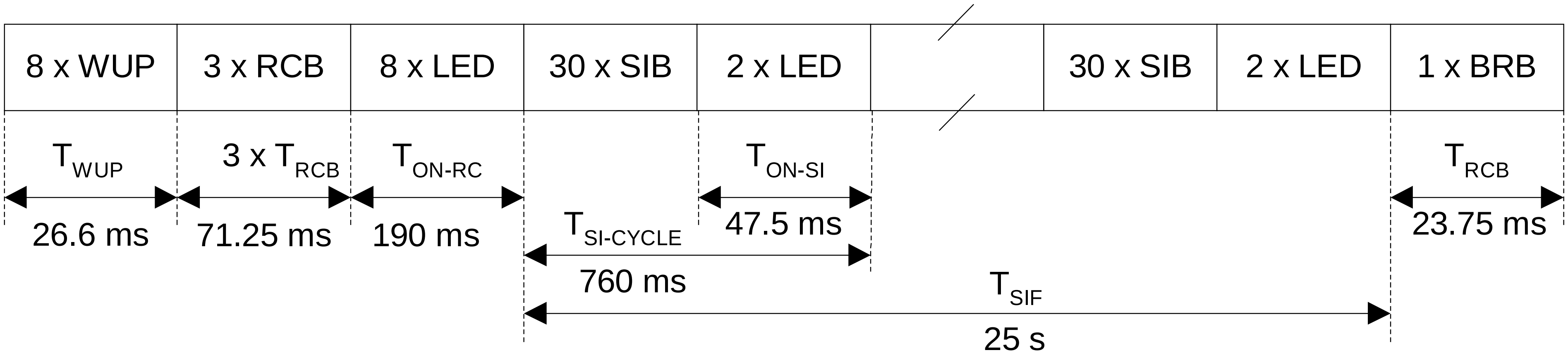
Design of an remote data telegram (2)

Hitag2+ data telegram format



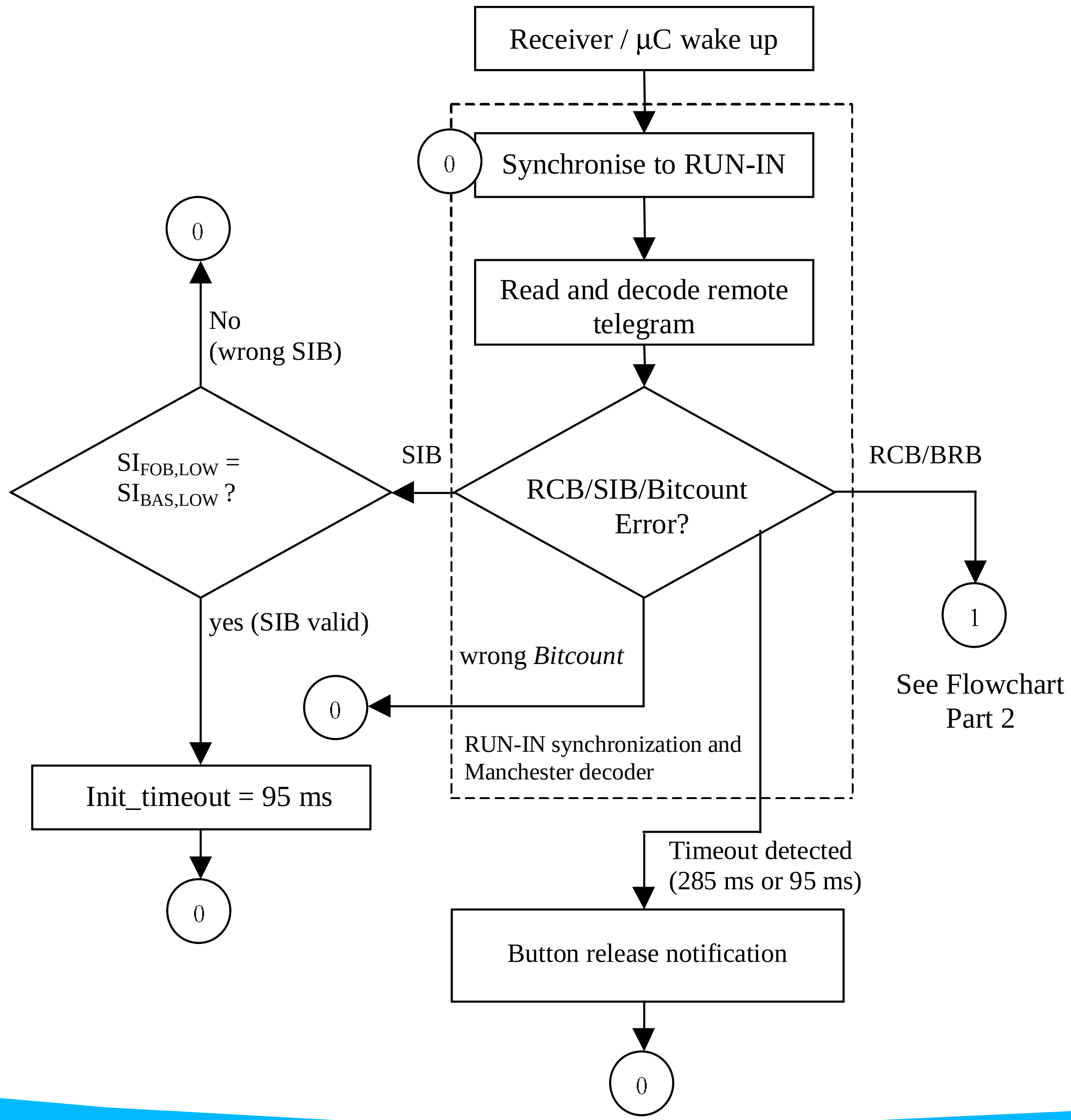
Design of an remote data telegram (3)

Example for a typical remote data telegram

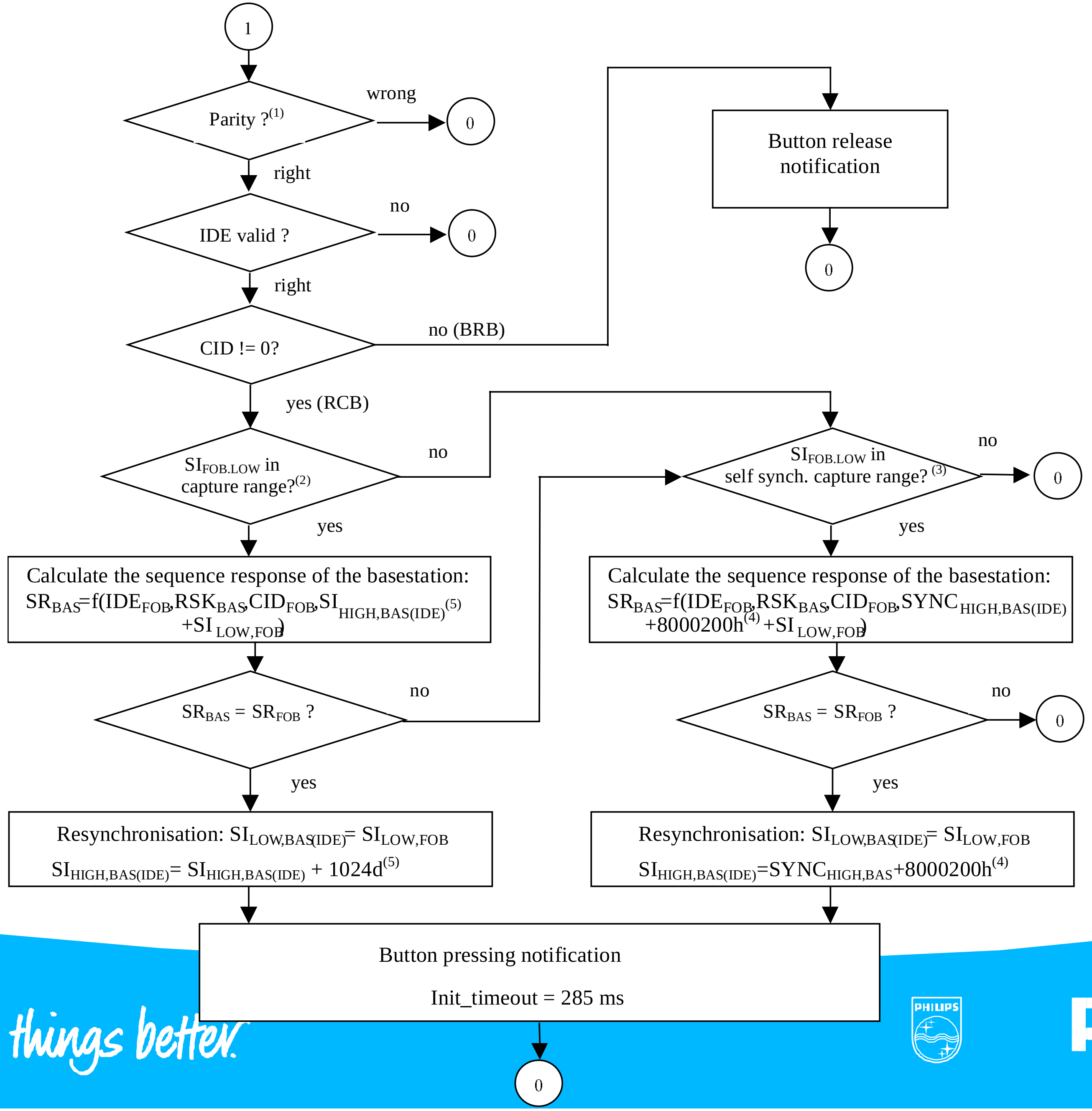


Immo-RKE-System-Design Version 4

Decoder and identification functions (1)



Decoder and identification functions (2)



Immo-RKE-System-Design Version 4

Appendix1: Overview about documents, software and tools, referenced in this presentation

Part1: Immobilizer Design

- Application Note AN99075: Designing RF-Identification Basestations with the Advanced Basestation IC PCF7991.
- User Manual and Software HSIS/UM9708: Control Software Library for PDF7991AT and PCF7936AS.
- User Manual and Tool: Transponder Evaluation and Development Kit (TED-Kit) HSIS/UM9907.
- Laboratory Report: Questions to the ABIC (PCF7991).
- Laboratory Report: Proposal for a Circuit Design and PCB-Layout for the PCF7991(ABIC).
- '*Product Qualification Packages*' of the particular products.

Appendix2: Overview about documents, software and tools, referenced in this presentation

Part2: RKE Design

- Application Note AN00041: Implementation of remote keyless entry with the PCF7946.
- User manual and Software CAS/UM0101: HITAG2 / HITAG2+ Security Algorithm for 8 bit microcontrollers.
- User Manual and Tool: Transponder Evaluation and Development Kit (TED-Kit) HSIS/UM9907.

Appendix3: Revision History

- Version 1 First Version
- Version 2 References to related documents, software and tools are given at the beginning of every chapter.
- Version 3 Chapter about the HITAG2+ RKE implementation added.
- Version 4 Chapter about worst case tolerance field simulations added.